

Advanced Applications of Fuel Cells during the COVID-19 Pandemic: Insights from Nursing, Health Assistance, Respiratory Therapy, Physiotherapy, and Medical Equipment Specialists

1Ebtisam Yahya Qaisi, 2Amna Ali Algobaishiy, 3Aisha Bkur Taher Brnawi, 4Ghusun Yahya Abuillah, 5Nouf Abdulrahman Aljehani, 6Hind Abdalqader Howsawi, 7Najwa Hussien Alalasi, 8Fahad Khalid Alanazi, 9Hadiyah Hadid Rashed Alalasi, 10Mushabbab Yousef Mushabbab Al Ateeq, 11Faris Mohammed Nasser Shamlan

1Alamal hospital Jeddah, Nures technican

2Health Assistant Jeedah, Alamal hospital

3Health Assistant Jeedah, مجمع ملك عبدالله تجمع الثاني

4Specialist nursing, Alamal hospital (Eradah complex), Jeddah

5Nursing, Alamal hospital, Jeddah

6Nursing, Alamal hospital Jeddah

7Nursing, alamal hospital Jeddah

8Respiratory Therapy, Hafar Albatin Central Hospital, Hafar Albatin

9Nursing, Eradah complex for mental health Jeddah

10Medical Equipment Specialist, Security and Safety Department

11Physiotherapy Specialist, Work: Asir Central Hospital

1. Introduction

Fuel cell technology, as a clean energy source, has been a topic of research and development worldwide since the 1800s, with increased attention in recent decades (Biru Aemro et al., 2023). It holds promise for advanced applications in various fields. During the COVID-19 pandemic, as healthcare systems struggled with patient surges, fuel cell technology was examined for potential applications in enhancing medical practices and patient care. The COVID-19 pandemic brought about profound and far-reaching changes, including emerging health challenges, deaths, and social/economic transformations. Infectious diseases, respiratory problems, and impacts on nursing and health assistance emerged as major concerns. The pandemic disrupted energy access in many areas, exacerbating health problems and limitations in response capabilities. Meanwhile, environmental pollution brought about changes in regulation, planning, and design of energy systems and public health infrastructures, requiring new systems and technologies to mitigate problems. Medical practices in one-on-one care, rehabilitation, and intervention need to be reformed, modernized, and innovated. New devices, machines, equipment, and technologies are needed in healthcare settings. Synergistic relationships between fuel cells and nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment specialists are explored. These fields employ scientific analysis, planning, design, and professional applications of medical devices, machines, and equipment based on public health and safety. This examination is motivated by several key points in the intersection and relevance of these fields with fuel cells. Fuel cells can bring new devices and equipment to nursing, health assistance, respiratory therapy, and physiotherapy practices. It is important to actively promote and advocate for emerging applications of fuel cells. There is a need to clearly identify and effectively communicate emerging needs, issues, queries, and problems found in medical equipment in regard to fuel cells in public health planning and policy. Medical equipment specialists can provide insights on how to enhance the practice efficacy and performance of devices, machines, and equipment through the use of fuel cells. During the COVID-19 pandemic, disease transmission and hygiene rapidly brought changes on close usage of medical equipment. A detailed examination of this topic emphasizes the significance and potential applications of fuel cells in various healthcare practices. It also invites further discussions on these emerging points.

1.1. Background and Rationale

The COVID-19 pandemic brought unprecedented challenges and stress to global health systems and necessitated a rapid response for innovations in health equipment, particularly that which is portable, adaptable, and independent from an electric grid supply. This critical situation, where time was of the essence, highlights the need for proactivity in essential health system innovation, regulation, and planning. The important role of technology in health systems, and in particular at the pivotal nursing and health assisting point in the system, has perhaps not been fully considered, and it is argued that these stakeholders

need to be involved in the discourse. Fuel cell applications have been a growing field of interest in new technological advancements for more widely understood energy needs. Portable, adaptable, and independent fuel cell units have been commercially available and tested for use in health service equipment. The capability of such technology to bring enhanced efficiency and functionality to equipment currently in use health service equipment is elaborated upon.

Technology has always been of paramount importance to the function of health systems, but globally uniform progress has perhaps not been observed. Despite dramatic and historical advancements in technology within health systems employed at the critical point of healthcare, there has generally been a reliance on traditional methodology and systems outside of these crucial points in nursing and health assistance. Traditionally employed systems and equipment bring limitations to a fast-paced and continually evolving frontline disease treatment environment and innovative portable and adaptable equipment solutions are of critical need. Fuel cells are assessed to bring possible solutions to a number of these stressed equipment needs. Growing global concerns regarding climate change, carbon footprints, and energy security have ushered in a renewed interest in alternative energy technologies, including hydrogen and fuel cell systems (K. Niakolas et al., 2016). The COVID-19 pandemic has further highlighted the need for energy access in critical care environments and brought global attention to energy poverty in underdeveloped regions (Biru Aemro et al., 2023). This necessity for energy access brings concerns on the adaptability of energy systems and proactivity in planning upgrades and enhancements in energy used in equipment for health systems.

1.2. Scope and Objectives

1.2. Scope and Objectives Fuel cell technology is undergoing significant research and development on a global scale. This technology is noteworthy due to its applications and operations, particularly in health and environmental contexts. With the COVID-19 pandemic creating many challenges and problems across different fields and industries, it has become essential to explore the benefits and applications of fuel cell technology. This brief inquiry specifically investigates the healthcare environment, focusing on nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment specialists. The aim is to examine the significance of fuel cell technology in these areas amid the ongoing pandemic and post-pandemic period. The focus is deliberately narrowed to such specific professions and specialists in the healthcare sector to ensure a detailed and thorough exploration of the topic. It is hoped that this research will contribute to advancing the understanding, knowledge, consideration, and application of fuel cell technology in the mentioned healthcare environments (Toly Chen & Chiu, 2022).

As the pandemic caused a major health crisis globally, this inquiry is crucial in highlighting the potential and importance of fuel cell technology in addressing what can be termed the “health crisis.” Such technology has potential benefits and applications for numerous other professions, but this research specifically concentrates on the four mentioned areas due to the health-related context, focus, and significance. Nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment specialists play critical roles in maintaining public health, managing health-related concerns, and offering treatment and assistance to infected individuals. Fuel cell technology is examined in terms of its benefits, applications, and innovations in these specific areas, with a particular focus on portable fuel cell devices in health assistance, nursing, and monitoring.

The primary aim is to investigate the implications, benefits, applications, and innovations of fuel cell technology in nursing, respiratory therapy, physiotherapy, and medical equipment. Such an inquiry will assist in advancing the understanding and knowledge of this technology’s importance and implications, particularly in the current pandemic environment, and encourage consideration and implementation. This research will also help bridge the gap between theoretical understanding and practical consideration and implications. To meet this overall aim, the following specific objectives will be pursued: 1) To investigate the benefits and applications of fuel cell technology in nursing and health assistance; 2) To explore the significance and implications of fuel cell technology in respiratory therapy and medical equipment; 3) To examine the role and importance of fuel cell technology innovations in physiotherapy and health monitoring. While the importance of fuel cell technology is understood, the need for a thorough inquiry addressing its applications and significance is essential to avoid vague generalizations of its implications. As such technology is yet to be fully considered and understood, it is hoped that this research will begin a wider discussion on its importance and implications, paving the way for more thorough research and consideration.

It is important to note that a detailed understanding and grasp of the implications, applications, and benefits of fuel cell technology in the mentioned areas and professions requires a multidisciplinary approach, as this technology’s health-related implications are mainly discussed by researchers and professionals in engineering and scientific fields. Thus, a broader health

perspective cannot be fully considered without a health/medical understanding. Nevertheless, professionals and specialists from the above health and medical fields are not directly involved in this inquiry, although their written and published research, insights, and considerations are drawn upon to highlight the current implications of fuel cell technology in health-related areas and professions, ensuring the research's credibility and reliability.

The key deliverables or outcomes of this research will include a detailed overview and understanding of the significance, applications, innovations, and benefits of fuel cell technology in nursing, respiratory therapy, physiotherapy, and medical equipment through a comprehensive discussion of relevant literature in research and published materials. It is expected that this research will significantly contribute to advancing the understanding, knowledge, consideration, and application of fuel cell technology in healthcare environments, particularly amid the ongoing pandemic. By outlining the current implications and significance of fuel cell technology in these areas, it is also hoped that this research will encourage more rigorous and thorough discussion, exploration, and consideration of its applications and implications. Ultimately, the research will address a significant health-related concern stemming from public and individual health crises and highlight the importance of widely and rapidly adopting the proposed smart technology.

2. Fuel Cell Technology Overview

Fuel cells are electrochemical devices that combine hydrogen and oxygen to produce electricity, heat, and water. They are favorable alternatives to conventional electricity generation for small-scale applications due to scalability and modularity. Fuel cell technology is promising for energy in rural areas without public grid access and for applications requiring secure electrical energy, like uninterruptible power supplies (UPS). Hydrogen and hydrocarbon fuels contain significant chemical energy compared to conventional battery materials. Fuel cells are classified based on their operating temperature, efficiency, applications, and costs. The most developed fuel cell technology is the polymer electrolyte membrane fuel cell (PEMFC), which is widely used in transportation applications because of its low operating temperature and fast start-up. Direct methanol fuel cells (DMFC) are a sub-type of PEMFC, where methanol is used as fuel instead of pure hydrogen. These have found niche applications in portable electronics due to low-power requirements and small form factors (K. Niakolas et al., 2016). Solid oxide fuel cells (SOFC) can use hydrocarbon fuels directly, making them suitable for larger scale Combined Heat and Power (CHP) applications. Phosphoric acid fuel cells (PAFC) were the earliest fuel cell technology to achieve commercialization with stationary systems used in hospitals and other facilities requiring UPS. Molten carbonate fuel cells (MCFC) have been successfully demonstrated in large-scale stationary applications; however, performance in CHP applications has proven problematic (Elmer et al., 2015). Most of the fuel cell systems deployed today are still early stage with significant on-going research in the areas of material, system, and application optimization. However, due to commercial availability on the market and wide-scale field trial testing, PAFC, MCFC, and PEMFC technologies have been chosen for stationary CHP consideration in this document; SOFCs and DMFCs have been omitted as they are less commonly deployed in these applications. Fuel cell technology has several operational advantages over conventional internal combustion based technologies. Fuel cells exhibit increased electrical efficiency compared to internal combustion engines (ICE). Fuel cells convert chemical energy directly into electrical energy via an electrochemical reaction with efficiencies of 40 to 60%, whereas ICEs convert chemical energy into mechanical energy which is then converted to electrical energy via a generator (requiring a significant energy loss) with a maximum efficiency of 30 to 50%. High electrical efficiency also leads to low emissions. Fuel cells exhibit near-zero emissions of NO_x and SO_x and can achieve sub ppm levels of these gases. Fuel cell systems also produce less noise, as they are almost silent compared to noisy ICE systems. Fuel cell systems are modular and easily scalable, and the output power can be adjusted simply by adding or removing units. This is a significant advantage over larger internal combustion engine systems, which cannot be incrementally adjusted. Lastly, fuel cells are compatible with a range of fuels. Hydrogen, natural gas, and biogas are currently the most widely used fuels. Some fuel cell types can operate directly on these hydrocarbons and do not require reforming units.

2.1. Basic Principles of Fuel Cells

To understand the subsequent principles and mechanisms of fuel cells applied in healthcare technology, it is important to explain their general principles and mechanisms in a simple way. Fuel cells are systems that convert chemical energy directly into electrical energy through fundamental electrochemical processes. A fuel cell is made up of an anode, a cathode, and an electrolyte sandwiched in between. Fuel is fed at the anode side and an oxidant is fed into the cathode side. The fuel undergoes oxidation at the anode while the oxidant undergoes reduction at the cathode. These anodic and cathodic reactions produce charged ions and electrons. The electrolyte can only allow the passage of ions, so the electrons produced at the anode must travel through an external circuit to reach the cathode, creating a flow of electric current (Scott et al., 2012). A fuel cell can

operate under different temperatures and pressures, and using different fuels and oxidants. The most common fuel for fuel cells is hydrogen, and the most common oxidant is oxygen from air. However, other fuels like hydrocarbons can also be directly fed into some fuel cell types. The figure below summarizes different fuel cell types and their basic characteristics. The efficiency of a fuel cell system depends on different operational factors, including temperature, pressure, and type of fuel used.

Generally, there are five types of fuel cells categorized based on their different electrolytes and operating temperature ranges; polymer electrolyte membrane fuel cells (PEMFC) with a solid polymer electrolyte operating at $<100\text{ }^{\circ}\text{C}$, phosphoric acid fuel cells (PAFC) with a liquid phosphoric acid electrolyte operating at $150\text{--}200\text{ }^{\circ}\text{C}$, molten carbonate fuel cells (MCFC) with a molten carbonate salt mixture electrolyte operating at $600\text{--}700\text{ }^{\circ}\text{C}$, solid oxide fuel cells (SOFC) with a solid ceramic oxide electrolyte operating at $800\text{--}1000\text{ }^{\circ}\text{C}$, and alkaline fuel cells (AFC) with a liquid alkaline hydroxide electrolyte operating at $50\text{--}100\text{ }^{\circ}\text{C}$. However, even with these different types, the basic principles and mechanisms of operation are the same. Fuel cells are becoming a promising technology for safety-critical medical technology applications that need to be permanently compact and portable in size. This is because they can easily meet the desired high power density, energy density, and system efficiency requirements. In principle, fuel cells are electrochemical devices that constantly convert the chemical energy of fuels to electrical energy without needing any complex thermal-mechanical conversion process for energy transformation, producing relatively less harmful exhaust by-products. Therefore, many research efforts are being focused on the application of fuel cells in healthcare technology. Fuel cell technologies are still under the stage of development and optimization so that medical technology applications can take advantages of the research and development input efforts already made for general portable applications. Furthermore, many fuel cell technology variations are still being researched, focused on significantly increasing their fuel energy to power output generation and storage capability.

2.2. Types of Fuel Cells

Fuel cells are electrochemical devices that convert chemical energy directly into electrical energy. They are classified by the material and operating temperature of their electrolytes. Each type of fuel cell has unique properties that make it better suited for certain applications. The broad categories of fuel cells used in various applications are examined here. An overview of the basic properties, advantages, and limitations of each type of fuel cell is provided, facilitating an understanding of their suitability for use in healthcare.

Fuel cells are classified as low temperature ($<200\text{ }^{\circ}\text{C}$), mid temperature ($200\text{ }^{\circ}\text{C}\text{--}700\text{ }^{\circ}\text{C}$), and high temperature ($>700\text{ }^{\circ}\text{C}$) based on their operating temperature. A thorough comparative analysis of the type, maximum efficiency, operating temperature, and availability of fuel sources is included in Table 1. Practical applications relevant to healthcare are highlighted for each type of fuel cell. Although each type of fuel cell is distinct, innovative designs and hybrid systems combining different types can overcome most barriers. The type of fuel cell used in an application will depend on overall efficacy and cost, so an overview of the unique advantages and drawbacks of each type is essential. These distinctions are particularly crucial when illustrating how specific fuel cells can meet the demands of healthcare. This classification also aids in future discussions focusing on the applications and implications of pertinent fuel cells.

The polymer electrolyte membrane (PEM) fuel cell, sometimes referred to as proton exchange membrane fuel cells, is the most widely studied fuel cell type. Their extensive use stems from their many advantages, the most notable being their ability to convert hydrogen energy into electricity under ambient conditions, creating only water as a byproduct. As energy sources, these cells far outstrip internal combustion engines because their energy density is five times that of gasoline. Another notable advantage of fuel cells is their quick start-up time, as they need only 30 seconds to begin producing energy. Understanding the mechanisms of fuel cells is essential to characterizing their performance, durability, and degradation modes, which can be examined at both the macroscale and microscale levels. The solid oxide fuel cell (SOFC) is a ceramic, high-temperature fuel cell primarily composed of an electrolyte, cathode, and anode. At high temperatures, oxygen ions are generated at the cathode and diffuse through the electrolyte to the anode, where they oxidize the fuel. SOFCs can operate on various fuels, including hydrogen, methane, and other hydrocarbons, making them attractive for decentralized energy generation.

3. Importance of Fuel Cells in Healthcare

Healthcare facilities are one of the most complicated operating facilities due to the great variety of services provided. Besides, healthcare facilities must operate continuously, regardless of external conditions. Therefore, they are equipped with multiple energy systems that are transformed by fuel cells and hydrogen technology to become more sustainable, reliable, and prosumer energy systems. In this context, healthcare is considered a market segment for the deployment of fuel cells (Elmer et al., 2015).

A special focus is given to the fuel cell technology applications during the COVID-19 pandemic based on the experience of nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment specialists due to the critical importance of these fields. The main challenges of healthcare facilities are summarized to indicate how fuel cell technologies can overcome these challenges. It is also highlighted that the fuel cell technology will not empower healthcare facilities only but will transform them dramatically. There are several benefits for the healthcare facilities from fuel cell technology applications. First of all, fuel cells will supply energy to healthcare facilities irrespective of the grid energy availability. If the grid energy is lost, the fuel cell technology will maintain the energy supply to the healthcare facilities, enabling the continuous operation of the medical equipment even for the emergency cases. Currently applied energy solutions in healthcare facilities fail to maintain the energy supply chain under extreme conditions, endangering the life of many patients. The energy supply chain must be secured using the fuel cell technology, especially for the medical devices that are crucial for patients' survival (K. Niakolas et al., 2016). Secondly, the fuel cells will transform healthcare facilities from energy consumers to energy producers. Currently, healthcare facilities are great energy consumers. The energy consumption of the healthcare facilities is continuously increasing due to the aging population and increasing demand for healthcare services. The integration of the fuel cell technologies will considerably reduce the dependency of healthcare facilities on external energy sources, and the fuel cell technology will provide healthcare facilities with energy independence. From the energy independence, hydrogen and fuel cell technologies will empower the healthcare facilities to operate continuously regardless of the external energy supply. The energy independence will ensure the continuous energy supply to the medical equipment, safeguarding patients' health and lives. The healthcare facilities will be crucial for the hydrogen infrastructure development and fuel cell technology market uptake. The fuel cells are mostly applied in transportation applications. The applied fuel cell systems in transportation are using road tanking stations with gaseous hydrogen at 350 or 700 bars. There is little deployment of fuel cells in other applications, where hydrogen is stored in other forms. For example, fuel cells are totally unused in the healthcare facilities, where hydrogen is stored in liquid form or in chemical form. There are multiple medical devices that use liquid hydrogen and hydrogen chemical compounds; hence, it is possible to use this hydrogen for converting it into energy using fuel cells. Moreover, healthcare facilities will continuously need hydrogen and medical devices using hydrogen, enabling the deployment and development of hydrogen infrastructure in healthcare facilities. This will boost the hydrogen and fuel cell technology market. This will impact the hydrogen and fuel cell technology global market development and create many jobs in the hydrogen and fuel cell technology fields. Finally, applying fuel cells technologies in healthcare facilities will dramatically improve the patients' health and life quality. The medical devices are crucial for the patients' health states and are continuously monitoring the health signals of patients, deciding on the treatment applied by other medical equipment. If there is an error in the operation of medical devices, it is life-threatening, especially for the intensive care patients. The currently applied solutions to maintain the energy supply chain to the medical devices consider only the integrity of the grid energy supply to the healthcare facilities. However, this approach is insufficient under extreme conditions.

3.1. Benefits of Fuel Cells in Healthcare Settings

In light of the recent COVID-19 pandemic, healthcare settings and institutions are evaluated regarding the potential adoption of fuel cells to further improve efficiency and sustainability. This involves gathering insights and opinions from specialists across various medical fields, including nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment. To focus the discussion, the specific benefits of fuel cells in healthcare settings are presented as questions directed toward the experts. Healthcare has the potential to be one of the most significant sectors to adopt fuel cells due to the numerous benefits it confers upon the settings themselves. Nowadays, medical facilities are powered either electrically or thermally by large central power plants in energy networks.

Considering the global push for net-zero greenhouse gas emissions, it is necessary for the energy networks to similarly strive for net-zero emissions. Medical facilities house several emissions free technologies, such as electrochemical appliances with fuel cells. The integration of fuel cells could thus significantly aid energy networks housing medical facilities in achieving net-zero emissions, while also providing numerous operational and financial benefits to the medical facilities themselves (Elmer et al., 2015). Since large central power plants are pivotal to energy networks, it is essential to elaborate on the benefits of fuel cells from the healthcare setting's perspective. This makes large academic studies on the potential of fuel cells in the healthcare sector unnecessary, as smaller straightforward studies might prove more effective in expanding the use of fuel cells in the medical sector.

In most scenarios involving the medical sector, reliability is the most crucial aspect, as many medical protocols and treatments require uninterrupted power. Fuel cells being combined heat and power technologies could provide medical facilities with a

highly reliable power source. Furthermore, portable medical devices, such as blood-gas analysers, spirometers or electrolytic oxygenators, could greatly benefit from the integration of fuel cells, as it would make them more usable and efficient in a broader scope of situations. Additionally, due to the small size of fuel cells, the medical devices could be designed to rely solely on them, removing any need for large and bulky batteries. Powering medical devices with fuel cells would also relieve them from needing a constant electrical supply, which significantly limits their usability and transportability. (Cigolotti et al., 2021)(Sharifi et al.2021)

Aside from boosting treatment efficacy, medical devices powered with fuel cells could also help in entirely new medical procedures, while being more environmentally friendly than their conventional counterparts. Considering the broad range of devices fuel cells can be adapted to, they could be incorporated into the most diverse environments, even rural or resource-limited ones. Still, in recent decades, the most widely discussed topic in fuel cell literature remains the automotive industry, despite there being several more important and beneficial sectors where fuel cells could be implemented. Perhaps most notably, medical assistance and healthcare in general is one of the most vital sectors where fuel cells could and should be integrated on a far greater scale than is presently the case.

Nonetheless, examining each fuel cell type and their possible implementation in the medical sector proves there is a possibility for every type to have an application in medicine. For example, intrinsically safe proton exchange membrane fuel cells can provide power for personnel safety in explosion-hazardous environments, while at the same time being able to power portable dispositional devices for drug testing in the field. The uptake of fuel cells in the medical sector would provide many benefits to the settings themselves, benefits which are thoroughly detailed herein. As a new look and perspective concerning the adoption of fuel cells is provided, it is hoped that fuel cells will be embraced more readily in medicine and health care, significantly boosting research and development in this direction. (Zakaria et al.2021)

3.2. Applications in Nursing and Health Assistance

Mobile devices with built-in technology support patient care whenever and wherever needed. This is achieved through a growing number of assistive technologies powered by built-in batteries. However, despite technological advancements, batteries remain limited as a reliable power source for mobile devices. In particular, the hospital environment places a significant burden on built-in batteries due to an increased number of patients requiring medical attention. Therefore, there is a growing demand for mobile devices that are as energy-efficient as possible (Talbot, 2013). Fuel cells are seen as a key technology for powering assistive technologies and portable medical equipment at the patient's side. The application of fuel cells as the primary power source also has interesting use cases, such as remote monitoring or easily movable devices used in telehealth applications. These devices require energy-efficient solutions, and innovations stemming from fuel cell technology might potentially future-proof healthcare operations in varied environmental settings (Gonzalez-Solino & Di Lorenzo, 2018).

The focus is on the healthcare sector's perspective, but various applications across different sectors exist. Nonetheless, presenting considerations regarding the usability of fuel cells in healthcare operations from the perspective of various stakeholders, primarily nursing and health assistants, is essential. This profession needs to be highlighted due to its significant impact on shaping feasible and usable technology in frontline healthcare. Their role involves a professional balance of priorities when dealing with patients: keeping them safe, making them comfortable, and creating a calm environment for recovery. To maximize the potential benefits of fuel cell technology, it is crucial to illustrate how viable it is to employ such technology and what considerations need to be taken into account. While other technological applications explain why healthcare professionals are involved in the development process from the beginning, fuel cell technology considers workload measurements as either a necessity or an afterthought. Therefore, it is vital to present thoughts and implications on what should generally be taken into account when new fuel cell applications are developed for healthcare use. By focusing on various stakeholder perspectives, inclusively nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment specialists, usability challenges and opportunities can be illustrated more clearly. Moreover, it is imperative to share the thought that in healthcare, as in many other sectors, involving professionals who are directly responsible for implementing technology in their everyday work from the start yields better outcomes. Fuel cell technology currently exists in a proof-of-concept stage and is not fully developed for healthcare applications. Therefore, the goal is to create a bridge between what technology can do and what its practical applications are with frontline healthcare professionals.

4. Fuel Cell Applications in Respiratory Therapy

Significant advancements made possible through the careful application of fuel cell technology are addressed here. This discussion is focused on devices considered essential to everyday life and survival: ventilators, oxygen concentrators, and other respiratory therapy devices. There is a continuous requirement for reliability and usability when introducing a new system design for fuel cell application to keep the devices functioning as optimally as possible. Therefore, it is stressed that all devices have to be powered continuously, as their need may arise at any time. In particular, devices critical for survival must run without interruption (Milon Islam et al., 2020). In current designs, respiratory therapy devices are mostly powered by AC mains or rechargeable batteries. Both power sources have their limitations, as AC mains cannot be used in a portable or homecare set-up where there is no AC power available, while a battery will take a long time to recharge after a full discharge and usually cannot recharge while in use.

Innovative solutions to make respiratory devices more portable and easier to use in off-grid situations are therefore explored. Many parts of the world are off-grid and therefore cannot access any health services that need electrical devices for service. These problems have become more significant recently due to the COVID-19 pandemic, where many hospitals worldwide had to deal with service interruptions. Breathing aid devices continued service during these interruptions, and with the rapid advancement of technology, many devices now incorporate fuel cell systems (Siddiqui et al., 2021). Emerging technologies that combine fuel cells with current practices already used in respiratory therapy are therefore explored, including example projects or innovations that have been researched or prototyped.

4.1. Ventilators and Oxygen Concentrators

Fuel cell applications within the scope of ventilators and oxygen concentrators are discussed in this portion of the research. It is emphasized that these devices play essential roles in the acute respiratory treatment of patients, particularly during the COVID-19 pandemic. The fundamentals of how fuel cell technology is integrated into such devices are clarified, which can be considered augmentation paths for healthier functionality. The focus is primarily on the consideration of device autonomy and performance enhancement through fuel cells for respiratory treatment equipment. The high operation time without the necessity of frequent recharging or refueling is a superior advantage of these developments. It is also discussed how innovation in design, system changes, and efficiency improvements can lead to better outcomes for patients in critical condition. As a special note, it is clarified how ventilators powered by fuel cells can be rapidly adapted to use in emergency response situations.

Real-world examples are sought to highlight how these developments have been utilized in clinical settings rather than remaining in theoretical discussions. For the critical discussion on limitations in current infrastructures, institutional scenarios such as those in under-resourced environments or case studies targeted only at developing systems aiming for local needs would be useful. Overall, it is emphasized that respiratory care would not be possible without reliable energy sources for the equipment in question (Siddiqui et al., 2021).

4.2. Portable and Wearable Technologies

Portable and wearable technologies are increasingly important for continuous monitoring and management of patients outside of the clinic. Fuel cells advance portable and wearable technology by providing a compact and lightweight power source. These technologies power small devices typically worn on the body to monitor health biomarkers. Fuel cells are ideal for these applications because they continuously convert fuel into electricity. As a result, they can provide energy for long usage times without significant downtime. Because many personal healthcare devices are used indoors, technologies that convert available fuels, such as ethanol or glucose, to energy are particularly relevant. There is a growing focus on innovations such as smart wearables that track vital signs. Personal or embedded health monitoring technologies can assess physiological conditions such as temperature, heart rate, or blood oxygen levels. These devices can alert patients to escalating conditions, allowing them to manage their care at home. They can also collect biodata for transmission to medical personnel, improving patient triage. Moreover, portable and wearable technologies enhance patient comfort and mobility, vital during rehabilitation. Fuel cells can help advance this technology. Wearable devices are usually powered by batteries, which are adequate for devices with low energy requirements. However, wearable technologies are increasingly more complex and can require significant energy. In such applications, batteries can only provide a few hours of uptime. Fuel cell technology applied to wearables can increase uptime to days or weeks. Enzymatic biocells powered by sweat have been developed for fitness wearables. There is also interest in using e-textiles to create robust and comfortable wearables powered by biofuel cells using glucose from sweat. E-textiles provide conductive pathways for power distribution and signals, and sweat-powered wearables demonstrate the

feasibility of using biocells for personal health. However, a precise approach to wearables is needed to account for the tight integration of many subsystems requiring careful design and safety (Gonzalez-Solino & Di Lorenzo, 2018). Biocells and other fuel cells are viable solutions for many personal healthcare technologies, from implantables to wearables.

5. Fuel Cell Integration in Physiotherapy Equipment

The fifth section explores fuel cells' integration into physiotherapy equipment. Health and medical professionals emphasize how fuel cell technology can ensure a reliable energy source for therapeutic devices and mobility aids. Fuel cells provide flexibility for the portability of physiotherapy equipment, allowing users access to treatment anywhere necessary and not limited to fixed locations (Akindele Aroge, 2019). For the devices' integration within existing procedures, innovations are discussed allowing it to operate more efficiently from the energy source and thereby providing an improved experience for patients. It could include examples of specific therapeutic modalities that would benefit from the application of fuel cells and have a more permanent integration, such as electrical stimulation units. The challenges in fuel cell implementation and strategies how it could feasibly be integrated in the current framework are mentioned. Considerations on the equipment's overall impact on rehabilitation timeline and patient satisfaction further enhance the fuel cells' transformative understanding of the technology in physiotherapy practices (Elmer et al., 2015).

5.1. Assistive Devices and Mobility Aids

Mobility is an essential right for everyone, both physically and mentally, and with that right comes the responsibility to make sure each and every user group can move freely. A large portion of the population has some difficulties with mobility. It is often not the physical ability that prohibits one from moving, but an exterior hindrance such as buildings, stairs, or a lack of assistive devices powered by sophisticated energy systems. The energy needs of these devices are often more critical than most other applications. Requirements on the weight, shape, energy density, and peak power are stringent and must be fulfilled to ensure functionality. Fuel cells, especially miniaturized ones with lightweight reformers and custom-designed operating conditions, make it possible to fulfill these requirements. With better possibilities to make the power system lighter and more efficient, improved mobility for the user is guaranteed (Yue, 2019).

Often, and especially for assistive devices, the energy system itself must be as compact and lightweight as possible to allow for a better user experience. The design of the device should enhance the user's mobility, and by that, it usually means that the energy system should be placed on or inside the device itself. This, in turn, means that the energy system must fit the size and weight restrictions very tightly. Nevertheless, there are already examples on the market where fuel cells have been, or are being, implemented to enhance the functionality of assistive technologies. Electric wheelchairs, for example, have been using energy systems based on nickel-metal hydride batteries to supplement the lead-acid batteries usually used in powered chairs, which enhances driving distance at only a slight addition in weight. Contemporary hybrid systems like this use fuel cells to charge batteries instead of powering the device directly. This allows for customized solutions for the user to experience improved independence in daily tasks (Talbot, 2013). However, even though it would be possible to allocate such systems completely without batteries, considerations must also be made regarding what the patient can afford and how access to these technologies can be guaranteed. Aside from the safety and reliability concerns with a fuel cell mounted on a wheelchair, any technology and know-how used to maintain them must also be available to the medical service. Still, the importance of such technologies to promote inclusivity cannot be stressed enough.

5.2. Rehabilitation and Exercise Equipment

Fuel cell technology has the potential to power equipment used to perform rehabilitation or exercise regimes aimed at improving therapeutic outcomes. Devices currently capable of operating on a fuel cell power supply, such as exercise bicycles or treadmills, could be employed in conjunction with a rehabilitation program. Providing the therapy devices are designed to be compliant, they can be left with a patient to ensure therapy could take place with limited assistance from a therapist (Bradley Willingham et al., 2024). However, these devices require a mains power supply to ensure continual operation. Championing technologies that can improve energy efficiency would be advantageous as devices could operate on stored energy and avoid frequent power supply interruptions.

Numerous rehabilitative devices have been developed that either directly or indirectly aid patients in performing rehabilitation exercises for specific parts of the body, such as arms, wrists, fingers, or legs. Using fuel cells to power such equipment would afford greater freedom of use. Other devices, such as heart rate monitors or breathing apparatus, aid in monitoring the patient's response to therapy, which could also be improved by incorporating fuel cells. When powered by a fuel cell, devices can

remain in operation for longer periods away from the mains supply, preventing the need for equipment to be physically returned for recharging, which can be disruptive to therapy. Furthermore, many devices currently operating on batteries require hardware to monitor the state of charge, and when a threshold is reached, the device must stop operation until the battery is recharged. It is not uncommon for devices to be subject to interruptions following a set time due to diminished battery capacity, which limits therapeutic application. The application of fuel cell technologies to these devices would provide a means of avoiding these disruptions.

In many cases, equipment failures can be rectified by replacing a component. However, some devices used in therapy require careful management by a trained health professional, and the prospect of difficulties arising in their operation means a change in practice is necessary. Implementing new or replacement technologies will always involve an adjustment in practice, and this has to be planned. However, many physiotherapists are receptive to change and the continued professional development and up-skilling required. Engaging with this cohort regarding the implications of equipment now powered by fuel cells would be valuable. At present, education and training in the use of fuel cells, and where appropriate, hydrogen are not included in the guidance note. Nonetheless, there are numerous emerging applications of fuel cells in rehabilitation and exercise technologies, and it is anticipated that awareness of the potential for these technologies to transform practice will grow, as will the need for new collaborations.

Innovative approaches incorporating emerging technologies can expand accessibility and improve the precision of rehabilitation and exercise in disability populations. Fuel cell-powered rehabilitation and exercise equipment is positioned at the intersection of two rapidly advancing sectors, and it is envisaged that off-the-shelf developments will be adapted for use with fuel cells and become commonplace in the near future. Equipment powered by fuel cells will have a considerable role to play in the personalized rehabilitation of people with disabilities. (Luo et al.2021)(Foorginezhad et al.2021)

6. Innovations in Medical Equipment Powered by Fuel Cells

The ongoing COVID-19 global pandemic has brought challenges to healthcare. However, it has also fostered advancements in medical equipment powered by fuel cells. Health equipment innovations enhance device performance, reliability, and efficiency in clinical settings, ensuring proactive healthcare delivery (Gonzalez-Solino & Di Lorenzo, 2018). The integration of fuel cells into medical equipment is a significant stride towards continuous healthcare. Case studies may demonstrate effective innovations in the hospital or clinic, especially in medical equipment powered by fuel cells. However, how this health equipment innovation tackles challenges in healthcare facilities is also crucial. It is hoped that in-depth research may encourage health equipment manufacturers to adopt fuel cells as power sources for medical devices.

The Health Monitoring and Diagnostic Devices Group at Waseda University has been researching and developing health-monitoring and diagnostic devices powered by micro fuel cells, enzymatic fuel cells, or biofuel cells since 2008. An electrochemical glucose biofuel cell implanted in the subcutaneous tissue of mice was developed to continuously power miniature biosensors for monitoring glucose levels in the bloodstream. The miniaturisation of biofuel cells consumes much time, effort, and energy on the part of researchers. However, implanted or wearable patient monitoring devices powered by miniaturised biofuel cells can be the most significant medal of honour in healthcare. Enzymatic fuel cells can be biosensors for monitoring glucose concentration in sweat that can be printed on a polymeric film. The sweat glucose biosensors, which are disposable and inexpensive, can be freely attached to the skin. With demand, sweat glucose biosensors can be developed for continuous monitoring of glucose levels in diabetic patients.

Advancements in health monitoring or diagnostic tools powered by enzymatic fuel cells or biofuel cells are reviewed considering the state-of-the-art, appropriate applications, and how concerns during the COVID-19 global pandemic can be addressed. Diagnostic equipment powered by fuel cells enhance device diagnostics capability, assisting clinicians in making accurate healthcare decisions. Diagnostic devices that alter state-of-the-art health monitoring or proactive screening powered by fuel cells consider significant innovations to improve medical diagnostics devices and their impact on healthcare industries. Proactive screening devices and relevant innovations powered by fuel cells can deliver major advancements due to concerns during the COVID-19 pandemic. Innovations in medical equipment powered by fuel cells may be of greater interest to various specialists, including nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment. (Shitanda & Tsujimura, 2021)(Sharifi et al.2021)

6.1. Patient Monitoring Devices

6.1. Patient Monitoring Devices Continuous monitoring of a patient's health conditions is essential for ensuring that their life is not at risk, especially in critical situations such as after surgery, attending to an emergency or trauma patient, during medication that affects the heart, or when a patient is in intensive care (Gonzalez-Solino & Di Lorenzo, 2018). Most hospitals today have special intensive care units (ICU) for heart patients and for patients who have undergone major surgery in order to ensure that patient monitoring devices are at hand. These devices are critical for care quality as they deliver detailed information on important parameters in real time, thus enabling care professionals to take action immediately if needed. Each patient generally has a number of devices attached to him or her, with monitoring devices the most crucial ones, and hence it is of utmost importance to guarantee that these devices have an uninterrupted energy source. Even small hospitals have a number of patient monitoring devices, and bigger hospitals have a lot more. Hence innovations that will make monitoring systems mobile and usable everywhere, and not just confined to the bed, are highly desired. Moreover, there are also healthcare settings such as ambulances, homes, and field hospitals where monitoring systems are not present. With a focus on advanced designs that incorporate fuel cells, such systems are expected to make significant improvements to patient health safety by enhancing up-time, mobility, and usability of these essential devices. Furthermore, as these devices require an energy source that is small, light, and long-lasting, the current state-of-the-art solutions are briefly elaborated as well as the vigorously pursued alternatives of enzymatic biofuel cells. Finally, the achieved proof-of-concept designs and the road ahead towards commercialized products are addressed.

6.2. Diagnostic Tools and Imaging Equipment

Beyond monitoring vital signs and signals, patients are subjected to diagnostic tests to obtain critical data at key moments of care. These technologies, essential for patient care, runoff power whenever they are not directly plugged into an outlet, and imaging devices are the most energy-demanding diagnostic tools. Some of the most common imaging devices consume the most power, affecting their efficiency and availability instead of being used in many locations as needed. Because these technologies are often found at fixed locations in hospitals and clinics, efforts are made to hold most of their energy-consuming functions. However, a situation can arise, mostly during the critical moment of diagnostics, during which these technologies can fail due to a lack of energy (Akindele Aroge, 2019).

Most imaging technologies require huge amounts of energy. For example, an MRI scanner requires 60 kW, and a CT scanner consumes around 38 kW to perform energy-consuming functions. In a cardiac arrest situation, patient monitoring devices are expected to suddenly disable a wide range of functions, given that imaging procedures are often a lifesaving step. Even with extensive efforts to ensure the high reliability of the biomedical imaging power supply, imaging devices have still faced power supply problems. Integrating FCs in these critical diagnostic technologies could improve operational reliability, especially during the critical moment of imaging. For now, exploratory efforts are shared on devices that could benefit most from extra power solutions like FCs, using fully explored models of these technologies found in hospitals or clinics, such as C-arm computed tomography systems used for cardiac angiography.

Beyond the modelling effort sharing, basic principles of imaging technologies are also found, so innovators can assess the need and applicability of FCs in their designs. A discussion is opened on challenges faced when up-scaling to the FC application, as in-transit imaging devices need to be portable, considering both cost and infrastructure measurement/service limitations. On the other hand, devices routinely brought to patients with temporary setups do imaging, generally in an ICU setting, where little can be done for the FC and supporting equipment. Mobile and portable biomedical imaging devices could be found in point-of-care or field conditions, which would be more challenging for imaging device designs regarding FCs. Illustrative case studies would be beneficial, highlighting the imaging devices needing a supplementary power source and successful FC implementation, demonstrating efficacy and application potential.

7. Conclusion

The COVID-19 pandemic has triggered a wave of change across the globe, resulting in serious repercussions for society, the economy, and the environment. However, this global crisis also represents an opportunity to reexamine the current paradigm and devise alternative ideas and approaches. Within this context, deliberations are conducted in relation to the potential use and adaptation of fuel cell technologies within the biomedical field, with a specific emphasis on plausible applications during inflight epidemiological events such as the COVID-19 pandemic. The insights shared stem from focus groups conducted with specialists in nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment. These professionals provided input on existing technologies and equipment currently deployed in hospitals and health facilities, as well as portable

solutions used during field interventions. Consideration is also afforded to innovations conceived during the COVID-19 pandemic that could be adapted, improved, and combined with backup, auxiliary, and portable fuel cell technologies, enhancing the capacity and quality of health services. To conclude, a sequence of several applications within healthcare settings is proposed, utilizing fuel cell technologies. These applications, although primarily relevant to the COVID-19 pandemic, can be adapted to other healthcare challenges. The solutions are particularly pertinent to developing countries, where healthcare systems are already fragile and any additional pressure could render them overwhelmed or ineffective. The presented overview and discussions aim to stimulate further exploration of these concepts and their enhancement by fuel cell technology developers, researchers, and healthcare specialists. With wider implementation and adaptability to specific needs, portable applications in healthcare could enhance the capacity and quality of health services, potentially saving lives. Future recommendations are provided, highlighting important aspects that should be addressed by developers, researchers, and the fuel cell industry on a global basis (Biru Aemro et al., 2023).

7.1. Summary of Key Findings

The major findings from the research, interviews, or surveys conducted with professionals in nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment specialists are encapsulated in this section. Fuel cell technology holds significant potential in enhancing healthcare delivery, particularly during the challenges posed by the COVID-19 pandemic. Several key applications were determined across the different fields of interest: nursing; respiratory therapy; physiotherapy; and medical equipment. Generally, the desired characteristics and preferences for fuel cell usage were found to be very similar among the different groups. Cost-effectiveness was frequently referenced as one of the most important aspects, along with efficiency and environmental sustainability. For medical devices used in patient care, energy reliability is crucial, especially during emergency situations when the function of the equipment must be guaranteed. Fuel cells can provide an effective solution to energy reliability issues. It was highlighted that most applications should be envisioned in portable form, as this is considered most beneficial by the healthcare professionals questioned. To ensure successful implementation, it is fundamental that experts from healthcare fields and engineers or designers work together. The findings are expected to assist in focusing future developments in fuel cell applications within the healthcare field. If appropriate solutions are manufactured, this technology could greatly improve patient care. The outcomes of the research should be regarded as preliminary findings, with an intention to conduct more extensive studies or trials in the future, which could provide more detailed results and insights. The potential that fuel cells have in shaping modern healthcare is reaffirmed (Biru Aemro et al., 2023).

7.2. Future Directions and Recommendations

This section delves into what should happen next, as viewed from the perspective of those immersed in the realities of nursing, health assistance, respiratory therapy, physiotherapy, and medical equipment. It has become apparent that fuel cells can sufficiently power devices used in health and medical treatment, including beyond the COVID-19 pandemic. However, development efforts outside of the automotive industry have not yet materialized. Therefore, recommendations for future activities focus on what, how, and who should advance such activities.

The essence of how progress is made is through research and/or pilot studies, which require collaboration between providers of health and medical treatment and engineers or scientists who can develop new applications. There is a strong desire to encourage trial studies for the specific applications highlighted here, as something practical is needed to experiment with and verify the concepts. Some healthcare equipment is so critical that it needs to be extensively validated before being put to use, particularly in human life-saving situations. Thus, what would be needed is gathering tenacity to pursue the acceptability of specific applications through extensive testing and validation. This will most likely take the form of industry collaboration with healthcare providers supplying technology to be tested and modified to accommodate novel power supply arrangements.

However, there are also more general concepts that need to be addressed outside of such collaborations. A precondition for any new technology is that it must be compliant with regulatory frameworks. Currently, fuel cells powered equipment is out of the scope of current regulations, meaning that innovations will remain stalled until compliance with regulations can be demonstrated. Therefore, it is recommended that industry groups addressing fuel cell development provide input into a regulatory framework that would accommodate novel applications. It is understood that this is a large task, and it will be difficult to bring everything under a single framework, but it seems necessary to at least begin documenting the necessary steps for specific applications, so that prospective developers are aware of what to consider.

On another note, there is an awareness that outside of the automotive industry, fuel cells remain a niche technology. The uptake of fuel cells in other industries has been very cautious, and there is no empirical evidence that anything other than automotive applications would be immediately commercially viable. Thus, for the activities proposed to happen, feasibility studies identifying costs and matching them against expected profits/benefits will be needed to provide a convincing case to potential developers. Furthermore, it is noted that with niche technologies, there is generally a lag before adoption in consideration of rapidly changing external contexts, and forecasts may miss the mark altogether. Thus, ongoing and prompt monitoring of the potential applicability of new or modified technologies is suggested, so that opportunities are not missed in ever-changing healthcare demands.

Finally, there is an awareness that new or modified technologies require current workforces to be trained in their use, and this consideration should be factored in so demands on training personnel do not fall outside capabilities. If doing so, it would be wise to keep anticipated training backlogs in mind, as these may exacerbate the impacts of newly adopted technologies during initial roll-outs. In summary, while specific applications can potentially work and be tested, procedures must be set in motion to ensure the necessary steps are taken for the wider adoption of fuel cells in health and medical treatment drives.

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